

TITLE: The role of volume-load in strength and absolute endurance adaptations in adolescent's performing high- or low-load resistance training

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Abstract

This study compared high- (HL) and low-load (LL), resistance training (RT) on strength, absolute endurance, volume-load, and their relationships in untrained adolescents. Thirty three untrained adolescents of both sexes (Males $n = 17$, females $n = 16$, 14 ± 1 years) were randomly assigned into either: 1) HL ($n=17$): performing 3 sets of 4-6 repetitions to momentary concentric failure; or 2) LL ($n=16$): performing 3 sets of 12-15 repetitions to momentary concentric failure. RT was performed 2x/week for 9 weeks. Change in maximum strength (1 RM) and absolute muscular endurance for barbell bench press was assessed. Weekly volume-load was calculated as sets [no.] x repetitions [no.] x load [kg]. 95% confidence intervals (CIs) revealed both groups significantly increased in strength and absolute endurance with large effect sizes ($d = 1.51-1.66$). There were no between group differences for change in strength or absolute endurance. 95%CIs revealed both groups significantly increased in weekly volume-load with large effect sizes (HL = 1.66, LL = 1.02). There were no between group differences for change in volume-load though average weekly volume-load was significantly greater for LL ($p < 0.001$). Significant Pearson's correlations were found for the HL group between average weekly volume-load and both strength ($r = 0.650$, $p = 0.005$) and absolute endurance ($r = 0.552$, $p = 0.022$) increases. Strength and absolute endurance increases do not differ between HL and LL conditions in adolescents when performed to momentary concentric failure. Under HL conditions greater weekly volume-load is associated with greater strength and absolute endurance increases.

Key Words: strength training; youth populations; workload; programming

INTRODUCTION

Resistance training (RT) is a mode of exercise known to have particularly wide ranging benefits in a variety of populations. Position stands providing recommendations for healthy and older adult populations have existed for some time (Pollock et al., 1998; Kraemer et al., 2002; American College of Sports Medicine, 2009). With a growing importance to develop favorable exercise habits earlier in life; these recommendations have extended to providing RT guidance for youths (Lloyd et al., 2014). Physical activity guidelines for youth populations across most nations and including the World Health Organization (WHO) also include recommendations for some form of muscle strengthening activity (e.g. RT) for health (WHO, 2016). RT, in addition to producing hypertrophy and strength gains, has been shown to improve a wide range of important health outcomes for adolescents (Faigenbaum & Myer, 2010; Faigenbaum et al., 2011; Lloyd et al., 2014) and is relatively safe (Faigenbaum & Myer, 2010; Fleck, 2011). Furthermore, recent research has shown that high muscular strength in adolescence is associated with a 20-35% lower risk of premature all-cause mortality (Ortega et al., 2012). Considering the potential value of increased muscular strength, studies examining the efficacy of RT protocols and indeed the variables important for optimizing such outcomes are of importance.

Optimization of strength and muscle mass through RT has been said to require the appropriate manipulation of variables such as: volume, load, frequency, rest intervals, repetition duration, muscle action, whether training is performed to momentary failure or not, exercise selection and exercise order (Pollock et al., 1998; Kraemer et al., 2002; American College of Sports Medicine, 2009; Fisher et al., 2011; Fisher et al., 2013). This is said to be the case for both adults and adolescent

populations as evidenced by the recommendations in the aforementioned organizational position stands. However, of these variables two which have received considerable interest in the scientific literature pertain to volume and load and indeed these have been argued as primary determinants of RT induced adaptations in youth populations (Lloyd et al., 2014).

Although volume is commonly considered in terms of either the number of repetitions or sets of repetitions across a period of time (e.g. per session or per week), this conceptualization does not consider the interaction between volume and load. Thus the concept of volume-load (i.e. sets [no.] x repetitions [no.] x load [kg]) has been argued as a useful measure to equate, or consider the impact of differences between, different RT protocols where volume AND/OR load differ. For example, greater volume-load has been argued by some as being of potential importance in driving the similar adaptations observed in low load (LL) RT protocols compared with high load (HL) protocols in adults when performed to momentary failure (Mitchell et al., 2012; Ogborn & Schoenfeld, 2014; Barcelos et al., 2015; Schoenfeld et al., 2015; Schoenfeld et al., 2016; Schoenfeld et al., 2016). Volume-load changes across the duration of an intervention have indeed been reported as greater in LL RT (Schoenfeld et al., 2016). However, whether this is a potential driver of adaptations in response to RT is not yet clear. The greater volume-loads of LL RT have been argued by some to induce greater accumulation of 'metabolic stress' and recruitment of lower threshold motor units (MUs) causing preferential type I fiber hypertrophy and similar whole muscle changes (Ogborn & Schoenfeld, 2014). Further, higher volume-loads might afford greater neural adaptations to enhance strength due to greater volume of practice repetitions. Counter to this it could however be argued that as

motor schema are load/force specific (Schmidt, 2003) the strength response would favor HL RT when the test of strength is similar to the training performed but that perhaps greater volume-load through LL training might better impact absolute endurance (Schoenfeld et al., 2015). However, much of the research and speculation in this area has pertained to RT applications in adult populations.

The most recent position statement on RT guidelines for children and adolescents present volume-load as the most appropriate way of conceptualizing RT dose and that its progression can be achieved through manipulation of either volume AND/OR load (Lloyd et al., 2014). Whether or not increases in volume-load are indeed sufficient or necessary for producing optimal adaptations in adolescents however is not presently clear. In addition, whether or not the proposed mechanism of increased volume-load during LL RT is responsible for the similar adaptations to HL RT is also unclear. Recent work has clarified that there are sex specific differences in adult populations in changes in volume-load over a short term (≤ 8 weeks) RT intervention (Ribeiro et al., 2015). However, men and women appear to produce similar strength adaptations to RT (Gentil et al., 2016) and so the effect of volume-load upon strength outcomes would appear minimal in this population. In young populations, for the majority of strength outcomes there is little difference between males and females (Lillegard et al., 1997). Whether the same can be said for adolescents where strength gains might primarily be related to neural adaptations (Lloyd et al., 2014), and thus where volume-load might play a more important role is of interest to examine, particularly in response to different RT loading schemes. Unfortunately there is a relative lack of research examining the manipulation of RT variables and thus volume-load changes upon adaptation in young populations. Young persons

have lower ability to recruit high threshold MUs compared with adults (Dotan et al., 2012) and so it might be expected that RT interventions maximizing synchronous recruitment of these MUs (i.e. higher loads) might enhance adaptation. Two studies from Faigenbaum and colleagues have examined the manipulation of load in young children (ages of ~5-12 and 8-12 years respectively). Faigenbaum et al (1999; 2001) examined a group performing HL (6-8 repetitions) compared to a group performing LL (13-15 repetitions) where participants trained to momentary failure. Interestingly the LL group had significantly greater increases in strength and endurance which may suggest an influence of the greater volume-loads performed by this group. Indeed the authors speculate that this may be due to greater practice of the movements performed enhancing MU recruitment. However, contrastingly a follow up study from this group reported that loads equating to repetition ranges of 6-10 (HL) or 15-20 (LL), also performed to momentary failure, produced similar improvements in strength, but only greater relative endurance improvements for the LL group. Though, changes in relative endurance favouring LL conditions may be a result of participants becoming more accustomed to the discomfort associated with such training (Fisher et al., 2016).

The present authors are not aware of any studies that have examined the correlations between both strength and absolute endurance adaptations and either average volume-loads or changes in volume-loads across an intervention in HL or LL RT. Nor have any studies examined the specific role of volume-load in adolescents in response to loading manipulations. Further, the use of heavier loading has not been examined in younger populations. Thus, the aim of the present study was to examine the role of volume-load in determining strength and absolute endurance

adaptations in adolescents over a 9-week HL (4-6 repetitions) or LL (12-15 repetitions) progressive RT intervention.

METHODS

Experimental Approach to the Problem

A randomized trial design was adopted with 2 experimental groups in order to examine the effects of high- and low-load RT in untrained adolescents upon changes in strength, absolute endurance and volume-load over a 9 week intervention. In addition the associations between changes in volume-load and both strength and absolute endurance were examined.

Subjects

To be included in the study, potential participants had to be 13-15 years old, at a maturation state between Tanner stages 3-4, had to have never taken part in a RT program and be free of health problems. Participants were excluded if they did not attend at least 80% of the training sessions (Gentil et al., 2013). The participants were asked to not change their nutritional habits (e.g., becoming a vegetarian, restricting caloric intake, or using nutritional supplements or ergogenic substances). Moreover, all adolescents were involved in moderate physical activity (e.g. jogging, agility or sports) for an average of 3 days a week a part of their physical education classes.

Power analysis of RT in adolescents without prior RT experience (6) was conducted to determine participant numbers (n) using a within participant effect size (ES), calculated using Cohen's *d* (1992) of 1.12 to detect improvements in muscular

performance. Participant numbers were calculated using equations from Whitley and Ball (2002) revealing each group required at least 13 participants to meet required power of 0.8 at an alpha value of $p \leq 0.05$. Thirty three untrained adolescents volunteered for the study. Participants were randomized to one of two groups: 1) a high load RT group (HL, $n = 17$), which involved 4 to 6 RM of eight resistance exercises; 2) or a low load RT group (LL, $n = 16$), which involved 12 to 15 RM of eight resistance exercises.

Informed parental consent and child assent were obtained prior to the study. They were informed about the experimental procedures and the benefits and risks of the study before signing a statement of written informed consent. The present study was performed in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki), and an Institutional Research Ethics Committee granted approval for the study.

Testing Procedures

The first three weeks consisted of familiarization with the training exercises, anthropometric assessment, and the testing of and re-testing maximum strength (1 RM) and muscular endurance. Maximum strength (1 RM) and muscular endurance on a barbell chest press was assessed at baseline (after the 3 week familiarization) and post-training. Additionally, subjects were asked to visit the laboratory at the same time of day to avoid circadian influences. They were also instructed not to take medications or supplements during the study period.

Maximal strength was determined by assessing 1 RM for the barbell bench press. Weight plates starting at 0.5 kg were used to adjust the load. On the testing day, subjects performed a warm-up consisting of 8 repetitions at 40 to 50% of their estimated 1 RM. After a 60 s rest interval, they performed 6 repetitions at 50 to 60% of their estimated 1 RM. Then, each subject had a maximum of 5 attempts to achieve his or her 1 RM load. All participants achieved a 1RM within the 5 attempts. The rest interval between attempts was 5 min. Range of motion was controlled for bench press exercise. Subjects had to touch their chest at the end of the eccentric phase and return to a position with their elbows fully extended at the end of the concentric phase. In addition, their neck, head, shoulders, and hips were kept in contact with the bench throughout the exercise, with their feet on the floor. Subjects received verbal encouragement throughout the test, and the same investigator performed all testing procedures. Test-retest reliability coefficient (ICC) was 0.97 for the 1 RM bench press test.

Absolute muscular endurance was determined by assessing the number of repetitions prior to failure for the bench press exercise at 70% of their 1RM. Prior to the test, subjects performed a warm-up consisting of 10 repetitions at 50% of their baseline 1 RM. Two minutes later, each subject carried out repetitions until failure at 70% of their baseline 1 RM (participants used the same absolute load for post testing i.e. 70% of baseline 1RM). Each repetition took 1.5 s for concentric and eccentric actions and was controlled by an electronic metronome. The test was finished when subjects were unable to keep up with the metronome pace. Range of motion was controlled as described above. The participants received verbal encouragement throughout the test, and the same investigator performed all testing

procedures. Test-retest reliability coefficient (ICC) was 0.94 for the absolute muscular endurance bench press test.

Training Intervention

During the first 3 weeks of the study participants underwent familiarization with the procedures of the study including the training interventions. During familiarization sessions, participants were instructed in how to correctly perform the exercises, and initial load values were obtained. Both HL and LL groups then performed the same resistance exercises twice weekly over the course of 9 weeks. All volunteers in both the HL and LL groups performed the same exercises using both free weights, body weight, and resistance machines (Gervasport, Cotia, Brazil): leg press, knee extension, barbell bench press, dumbbell fly, lat pull-down, seated row, crunches, and leg raises. The HL group performed 2 sets at 4 to 6 RM, while the LL group carried out 2 sets at 12 to 15 RM for each exercise. For crunches and leg raises, both the HL and LL groups performed 2 sets of 15 repetitions. The rest interval was 60 s between sets and 120 s between exercises for both groups. Subjects were instructed to perform 2 s for both concentric and eccentric muscle actions. Participants were also instructed to perform all sets until concentric momentary failure in order to control effort between groups (Steele, 2014). If necessary, loads were adjusted (± 5 -10%) at each set to maintain the desired number of repetitions from set to set and session to session if participants either exceeded or could not meet the desired repetition range. Weekly training sessions were conducted with a minimum of 48 h between sessions. Each participant completed a training log for each training session, containing the loads used and the number of repetitions performed in each set. All training logs were verified by a supervisor following every

exercise session. All training sessions were closely supervised by experienced and certified trainers (Gentil & Bottaro, 2010). Moreover, the participants were not allowed to perform any extra RT exercise.

Statistical Analysis

The independent variable in the present study was group (HL or LL) and the dependent variables of interest where the absolute change in body mass, stature, strength and absolute endurance in addition to the average volume-load and change in volume-load across the intervention for both the bench press exercise. Volume-load was calculated from participant training logs over the intervention period as sets [no.] x repetitions [no.] x load [kg]. Weekly volume-load was calculated and then average weekly volume-load obtained across the intervention and change in volume-load as the difference between the 1st and 9th week of training (week 9 minus week 1). Assumptions of normality of distribution where examined using a Shapiro-Wilk test. Data met assumptions of normality of distribution and parametric tests were utilized. Between groups comparisons using independent t-tests were conducted for change in strength and absolute endurance, in addition to average weekly volume-load and change in volume-load. For change in volume-load 95% confidence intervals (CI) were calculated in addition to within participant ES using Cohen's *d* to compare the magnitude of effects between groups where an ES of 0.20-0.49 was considered as small, 0.50-0.79 as moderate and ≥ 0.80 as large. Pearson's correlations were conducted both within the HL and LL groups individually and for the participant sample as a whole for change in strength and both average volume-load and change in volume-load, as well as change in absolute endurance and both average volume-load and change in volume-load. Correlation coefficients were

interpreted as weak ($r = 0.30$ to 0.50), moderate ($r = 0.50$ to 0.70) or strong ($r > 0.70$). Post hoc power calculations are also provided for tests ran. Statistical analysis was performed using SPSS (version 22; IBM, Portsmouth, Hampshire, UK) and $p \leq 0.05$ accepted as the limit for statistical significance.

RESULTS

Baseline characteristics

Sex ratio between groups was similar (male: females; HL = 10:7, LL = 7:9). Baseline demographic characteristics did not differ between groups. Independent t -test comparing between groups for these variables found no significant between-group differences for age ($t_{(31)} = 0.254$, $p = 0.801$; HL = 14 ± 1 years, LL = 14 ± 1 years; $\beta = 0.05$), stature ($t_{(31)} = -0.442$, $p = 0.661$; HL = 161.2 ± 7.3 cm, LL = 162.2 ± 5.2 cm; $\beta = 0.07$), body mass ($t_{(31)} = -0.718$, $p = 0.478$; HL = 54.7 ± 18.8 kg, LL = 58.6 ± 10.2 kg; $\beta = 0.11$), 1RM ($t_{(31)} = 0.217$, $p = 0.830$; HL = 31.4 ± 7.1 kg, LL = 30.9 ± 7.1 kg; $\beta = 0.05$), or absolute endurance ($t_{(31)} = 0.333$, $p = 0.742$; HL = 11.4 ± 4.5 repetitions, LL = 10.9 ± 2.3 repetitions; $\beta = 0.07$) supporting similar levels of maturation in both groups.

Change in body mass, stature, strength and absolute endurance

Independent t -test revealed no significant between-group differences in change in body mass ($t_{(31)} = 0.507$, $p = 0.616$; HL = -0.1 ± 1.8 kg, LL = -0.3 ± 1.1 kg), stature change ($t_{(31)} = 1.785$, $p = 0.082$; HL = 0.8 ± 0.7 cm, LL = 0.4 ± 0.5 cm), strength ($t_{(31)} = 0.276$, $p = 0.784$; HL = 4.6 ± 2.8 kg, LL = 4.4 ± 2.8 kg; $\beta = 0.05$), or change in absolute endurance ($t_{(31)} = 0.360$, $p = 0.721$; HL = 5.2 ± 3.2 repetitions, LL = 4.8 ± 3.6 repetitions; $\beta = 0.06$). Change in body mass were not significant within groups however 95%CI's indicated a significant increase in stature (HL = 0.4 to 1.2 cm, LL =

0.1 to 0.7cm). Figure 1 shows the mean changes in strength and absolute endurance as a result of the intervention with 95% CIs for each group indicating that changes were significant both groups. ESs for change in strength were large for both HL ($d = 1.64$) and LL groups ($d = 1.62$). ESs for change in absolute endurance were large for both HL ($d = 1.66$) and LL groups ($d = 1.51$).

Insert Figure 1 about here

Weekly volume-load and change in volume-load

Independent t -test revealed a significant between-group difference in average weekly volume-load ($t_{(31)} = -4.507$, $p < 0.001$; HL = $696.4 \pm 216.5\text{kg}$, LL = $1142.4 \pm 341.8\text{kg}$; $\beta = 0.99$). Figure 2 shows the mean change in volume-load between week 1 and week 9, with 95% CIs for each group indicating that significant changes in volume-load occurred within both groups. There was no significant difference between groups for change in volume-load ($t_{(31)} = -0.481$, $p = 0.635$; $\beta = 0.08$). ESs for change in volume-load were large for both HL ($d = 1.66$) and LL groups ($d = 1.02$).

Insert Figure 2 about here

Correlations between strength and volume-load

Pearson's correlations revealed no significant relationships between change in 1RM and both average weekly volume-load ($r = 0.093$, $p = 0.607$; $\beta = 0.42$) and change in volume-load ($r = -0.106$, $p = 0.559$; $\beta = 0.47$) for the combined groups. For the HL group there was a significant moderate relationship between change in 1RM and

weekly volume-load ($r = 0.650$, $p = 0.005$; $\beta = 0.99$) but not change in volume-load ($r = 0.174$, $p = 0.504$; $\beta = 0.40$). For the LL group there were no significant relationships between change in 1RM and weekly volume-load ($r = -0.165$, $p = 0.542$; $\beta = 0.36$) and change in volume-load ($r = -0.266$, $p = 0.319$; $\beta = 0.56$). Figure 3 shows scatter plots for all average weekly volume-load correlations and figure 4 shows scatter plots for all change in volume-load correlations.

Insert Figure 3 about here

Insert Figure 4 about here

Correlations between absolute endurance and volume-load

Pearson's correlations revealed no significant relationships between change in absolute endurance and both average weekly volume-load ($r = 0.037$, $p = 0.837$; $\beta = 0.19$) and change in volume-load ($r = 0.067$, $p = 0.712$; $\beta = 0.31$) for the combined groups. For the HL group there was a significant moderate relationship between change in absolute endurance and weekly volume-load ($r = 0.552$, $p = 0.022$; $\beta = 0.96$) but not change in volume-load ($r = 0.339$, $p = 0.184$; $\beta = 0.73$). For the LL group there were no significant relationships between change in absolute endurance and weekly volume-load ($r = -0.166$, $p = 0.538$; $\beta = 0.36$) and change in volume-load ($r = -0.057$, $p = 0.834$; $\beta = 0.14$). Figure 5 shows scatter plots for all average weekly volume-load correlations and figure 6 shows scatter plots for all change in volume-load correlations.

Insert Figure 5 about here

Insert Figure 6 about here

DISCUSSION

Both volume and load are important variables to consider in RT and have been argued as being particularly important for youth populations (Lloyd et al., 2014). Further, their interaction, volume-load, has been proposed as the most appropriate way of conceptualizing RT dose in youth populations and that adaptations may be related to its appropriate manipulation. However, whether changes in this variable are in fact related to adaptations is not well understood. Volume-load can be manipulated via changes in loading strategies and the present study considered both HL and LL RT in an adolescent population to examine the relationships between volume-load characteristics and changes in strength and absolute endurance. Average weekly volume-loads performed were significantly higher in the LL group compared with the HL group. In addition, both groups significantly increased in the volume-load performed from week 1 to week 9 though there was no difference between groups. Both groups also significantly improved strength and absolute endurance with no between group differences. Finally, in the combined group data there appeared to be no relationship between either weekly volume-load or change in volume-load and either change in 1RM or change in absolute endurance. However, there was a significant moderate relationship between weekly volume-load and change in both 1RM and absolute endurance in the HL group.

That average weekly volume-loads were significantly greater in the LL group in the present study is not surprising. In studies of adult populations where effort is controlled between different loading conditions by having participants train to momentary concentric failure LL conditions consistently produce higher volume-load performances compared with HLs (Barcelos et al., 2015; Mitchell et al., 2012; Schoenfeld et al., 2015; Schoenfeld et al., 2016). In addition, where relative loadings are kept constant absolute volume-load typically increases over the course of a RT intervention due to participants' increases in strength (Ribeiro et al., 2015). Both the HL and LL group in the present study significantly increased in the volume-loads used from week 1 to week 9 though there was no significant difference in change between groups. This is in contrast to previous research in adult populations reporting the changes in volume-load over the course of a RT intervention in both HL and LL conditions. Schoenfeld et al (2016) found that there was a significantly greater increase in volume-load in a group performing LL RT consisting of 25-35 repetitions to momentary concentric failure compared with a HL group performing 8-12 repetitions to momentary concentric failure. Both groups effect sizes were large for change in volume-load though due to greater intra-individual variation in response was lower in the LL group (1.02) compared with the HL group (1.66) in the present study. The contrasting results between this study and that of Schoenfeld et al (2016) may be due to the differences in loading between the LLs and HLs compared. Schoenfeld et al (2016) compared two loading conditions that were farther apart than that compared in the present study (HL = 4-6 and LL = 12-15 repetitions to momentary concentric failure). Thus, the difference between conditions may have been far smaller. In addition, a type II error may have occurred whereby we did not

have sufficient power to detect small between group differences. A post hoc computation of achieved power for our comparison supported this ($\beta = 0.08$).

Both HL and LL groups in the present study significantly improved in both strength and absolute endurance with no between group differences. Sample size was adequate for detection of significant within group changes however post hoc power analysis revealed low statistical power for between group comparisons. Thus the lack of significant between group differences for improvements could be ascribed to a type II error. However, the absolute difference between the groups was very small and so it is likely that any difference is relatively meaningless. Further, most research to date suggests that when RT is performed to momentary failure adaptations such as strength and absolute endurance are likely to be similar (Barcelos et al., 2015; Mitchell et al., 2012; Schoenfeld et al., 2015; Schoenfeld et al., 2016). Most research to date however has seemingly been conducted with adult populations, including the elderly. Faigenbaum et al (1999; 2001) reported greater adaptations as a result of LL training compared with HL in young children participants who in their study only performed a single set per exercise. Though, the follow-up study from this group reported similar adaptations for strength and greater adaptations for only relative endurance in LL with single sets to momentary failure (Faigenbaum et al., 2005). Instead participants in the present study performed 2 sets of each exercise and results suggest there is no difference between LL and HL for younger populations also. Thus there may be some minimal threshold of volume-load required to optimize adaptations after which manipulations of load or volume have little effect if performed to momentary failure. The practical implications of this are important as it means that younger populations can utilize relatively lower loads to obtain optimal adaptations,

potentially reducing the likelihood and/or severity of injuries (Lloyd et al., 2014). However, whether or not these similar improvements in functional outcomes are the result of similar mechanisms has also been cause for speculation within the literature.

The greater increases in volume-load typically observed with LL RT interventions has been argued by some as being a possible driver of adaptations (Mitchell et al., 2012; Ogborn & Schoenfeld, 2014; Schoenfeld et al., 2015; Schoenfeld et al., 2016; Schoenfeld et al., 2016). Recent reviews and meta-analyses have reported that, when performed to momentary concentric failure, both HLs and LLs produce similar adaptations (Fisher et al., 2011; Fisher et al., 2013; Schoenfeld et al., 2016). Some have argued that the greater volume-loads accrued by LL conditions favor stimuli related to 'metabolic stress' and recruitment of lower threshold MUs causing preferential type I fiber hypertrophy and similar whole muscle changes (Ogborn & Schoenfeld, 2014; Schoenfeld et al., 2015; Schoenfeld et al., 2016; Schoenfeld et al., 2016). Though, whether or not there is preferential MU recruitment with different loads when performed to momentary failure is currently lacking evidence (Vigotsky et al., 2015). In addition, this greater volume-load could be argued to permit greater neural adaptations to enhance strength and endurance adaptations due to greater volume of practice repetitions. The results presented here however do not support the hypothesis that greater volume-load resulting from LL conditions are associated with the adaptive response in adolescents.

There were no relationships between either average weekly volume-load or change in volume-load and either change in strength or absolute endurance in the LL group.

Contrastingly, for the HL group there was a significant moderate positive relationship between average weekly volume-load and change in both strength and absolute endurance. In addition, though not significant, the scatter plots suggest a similar yet weaker positive relationship between change in volume-load and change in both strength and absolute endurance. Exactly why there were between group differences in the presence of a relationship between these variables is unclear. The relationship in the HL group is in contrast to the suggestion of Faigenbaum et al (2001) that LL may enhance adaptations through greater volume-load and greater practice of the movements performed enhancing MU recruitment. Whilst when both groups' data were combined there were no relationships; it could be speculated that these results suggest there may be different stimuli and adaptive mechanisms driving the similar adaptations seen in HL and LL RT when performed to momentary concentric failure.

Recent studies have reported higher peak electromyographical (EMG) amplitudes when comparing HLs with LLs performed to momentary concentric failure in adult populations (Schoenfeld et al., 2014; Jenkins et al., 2015; Looney et al., 2016). Though the authors of these papers interpret these findings to mean that MU activation is not maximal under LLs it is important to note that whilst EMG amplitude is influenced by MU recruitment strategies it is inappropriate to infer MU recruitment from amplitude data for a variety of reasons (Vigotsky et al., 2015; Enoka & Duchateau, 2015). The high EMG amplitudes reported during HL conditions may be reflective of high synchronous MU recruitment (both low and high threshold MUs) in order to produce high force. Whereas during LLs performed to momentary concentric failure only enough MUs sufficient to produce the required force would be recruited initially; yet, as those MUs fatigue other MUs would be sequentially recruited to

replace them in sustaining the desired force (Potvin & Fuglevand, 2016). Indeed, during fatiguing contractions the threshold for recruitment of higher threshold MUs is reduced permitting their subsequent recruitment (Adams & De Luca, 2003) and MUs may 'cycle' (momentary de-recruitment and recruitment of different MU) during submaximal fatiguing contractions to reduce fatigue and maintain force (Westad et al., 2003). Furthermore, the 'muscle wisdom hypothesis' suggests that during sustained contractions motor unit discharge rate might decrease due to optimizing the force output of motor units and protecting against peripheral conduction failure (Petrofsky & Phillips, 1985; Behm, 2004). Should this decrease in discharge rate occur, there would be a resultant decrease in EMG signal amplitude (Garland & Gossen, 2002). As such, whilst HL might require more synchronous MU recruitment at greater frequencies (resulting in higher EMG amplitudes), sustained contractions to muscular failure with LL might ultimately recruit all MUs albeit sequentially (resulting in lower EMG amplitudes) rather than synchronously (Fisher et al., 2016).

The relationship between volume-load and both strength and absolute endurance adaptations under HL conditions may thus reflect slightly different neural mechanisms relating to strength adaptation i.e. skill specificity in motor recruitment (Behm & Sale, 1993; Buckner et al., 2016; Fisher et al., 2016). Motor control research suggests that a motor schema is highly specific to the task being practised (Drowatzky & Zuccato, 1967; Mount, 1996), and motor schemata have also been reported to be *load/force* specific (Schmidt, 2003). With this in mind, lifting a HL in a particular movement might serve to practise and refine that schema as a skill which would include the maximal synchronous recruitment of MUs and the volume-load may bear a relationship to adaptations as a reflection of practice of this motor

schema. Indeed in younger populations there is a lower ability to recruit high threshold MUs and possible lower MU synchronisation during volitional contraction (Dotan et al., 2012). It could be speculated that this increased ability to recruit higher threshold MUs and particularly increase MU synchronisation might be a mechanism particularly responsive to HL in adolescents. Contrastingly the lack of relationship between volume-load and adaptations with LLs may indicate that, under these conditions, the recruitment strategy is less influential and as long as momentary concentric failure is achieved and thus maximal MU recruitment occurs, the preceding volume-load and any fatigue related stimuli may be inconsequential. However, the acute effects of HL and LL may differ in more than just MU recruitment strategies. Acute changes in muscle thickness and blood lactate (possibly reflecting cellular swelling and 'metabolic stress' related stimuli respectively thought to influence adaptations (Schoenfeld et al., 2010)) may differ between HL and LL at least in adult populations. Future research should look to examine relationships between possible stimuli such as these and the adaptations as a result of RT with differing loads in younger populations.

It should be considered that the present study was conducted in adolescents and thus the results may not be applicable to adult populations. Strength gains in inexperienced adolescents are thought to be primarily related to neural factors (Lloyd et al., 2014) and as such the influence of volume-load upon adaptations may differ in adult populations. Further research should look to examine whether similar relationships do indeed occur in older populations.

The limitations of the present piece should be considered. Though Tanner stages were controlled and no change in body mass was noted, it is difficult to determine whether the strength and absolute endurance changes observed were the result of the intervention or maturation over the intervention period. Both groups increased significantly in stature, though there was no significant between group difference. The absence of a non-training control though prohibits sole ascription of the strength and absolute endurance changes to the training intervention alone.

CONCLUSIONS

The results of the present study suggest that, though average volume-load between HL and LL RT differs, changes in volume-load over a RT intervention using HL or LL do not. In terms of the relationships between volume-load characteristics and changes in strength and absolute endurance, there appears to be a relationship under HL conditions; greater weekly volume-load is associated with greater strength and absolute endurance increases. However, strength and absolute endurance increases do not differ between HL and LL conditions in adolescents when performed to momentary concentric failure. Thus, the presence of a relationship between volume-load and adaptations for HL conditions may indicate differential adaptive mechanisms are responsible.

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest associated with this manuscript.

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Figure Captions

Figure 1. Mean change in strength and absolute endurance with 95%CI

Figure 2. Mean change in volume-load with 95%CI

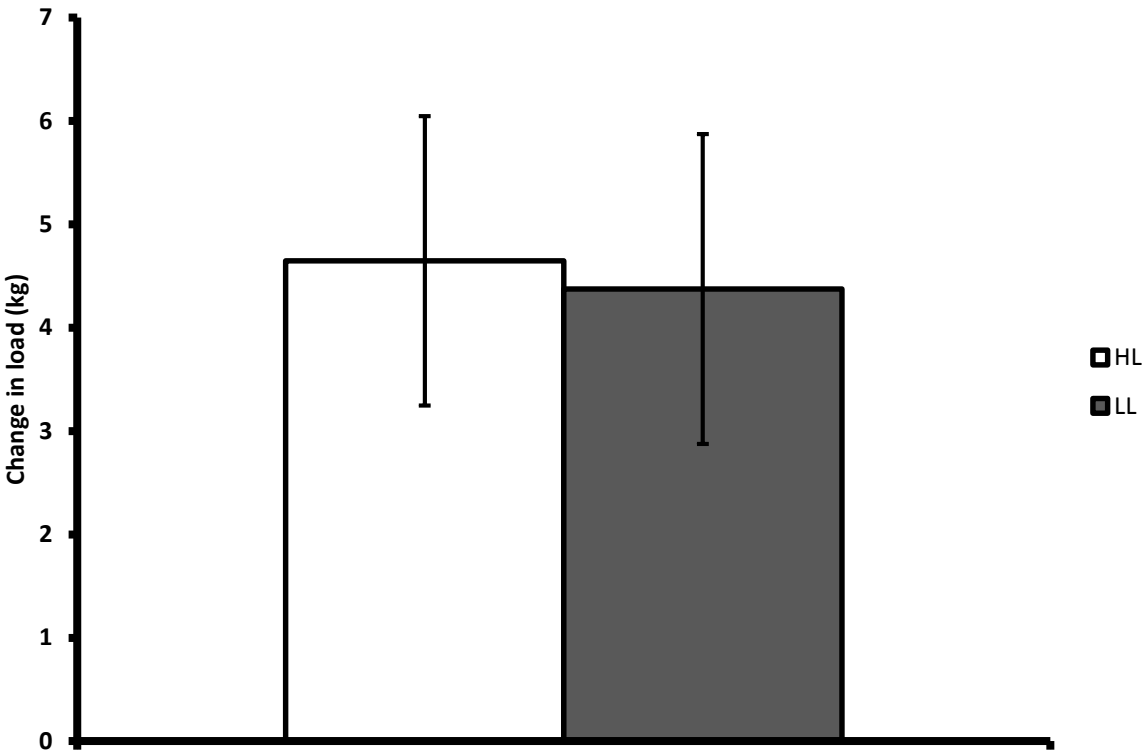
Figure 3. Scatter plots for average weekly volume-load and change in strength for A) HL group, B) LL group, and C) combined groups

Figure 4. Scatter plots for change in volume-load and change in strength for A) HL group, B) LL group, and C) combined groups

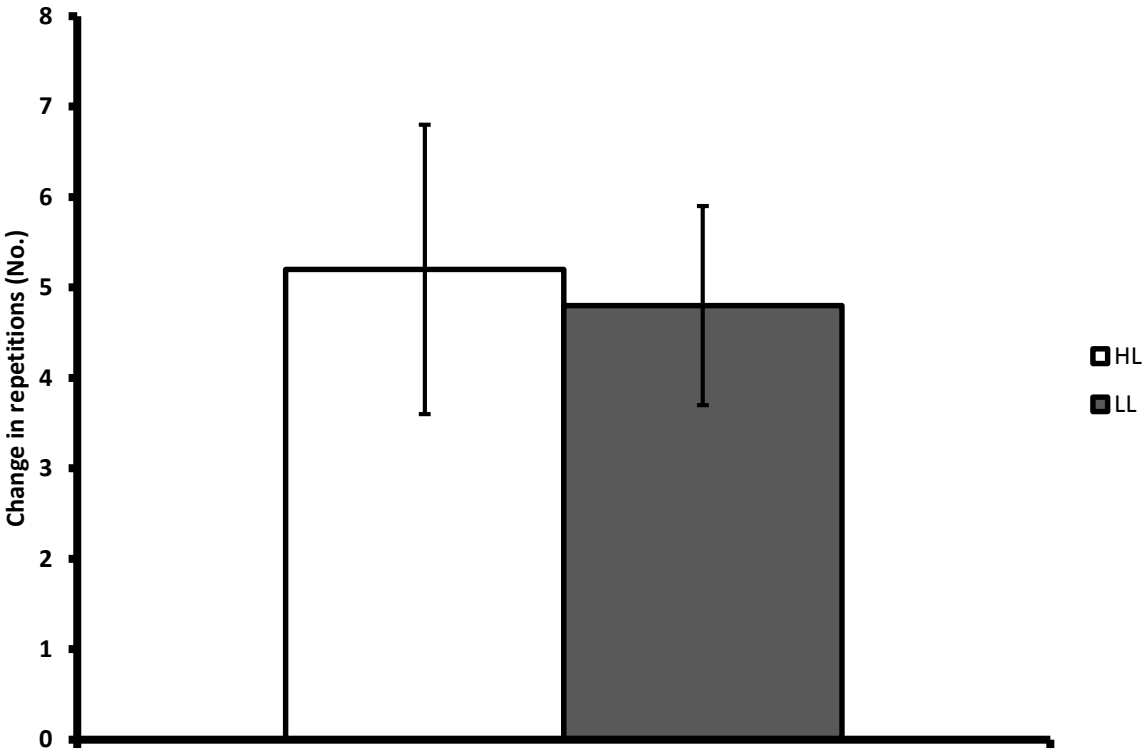
Figure 5. Scatter plots for average weekly volume-load and change in absolute endurance for A) HL group, B) LL group, and C) combined groups

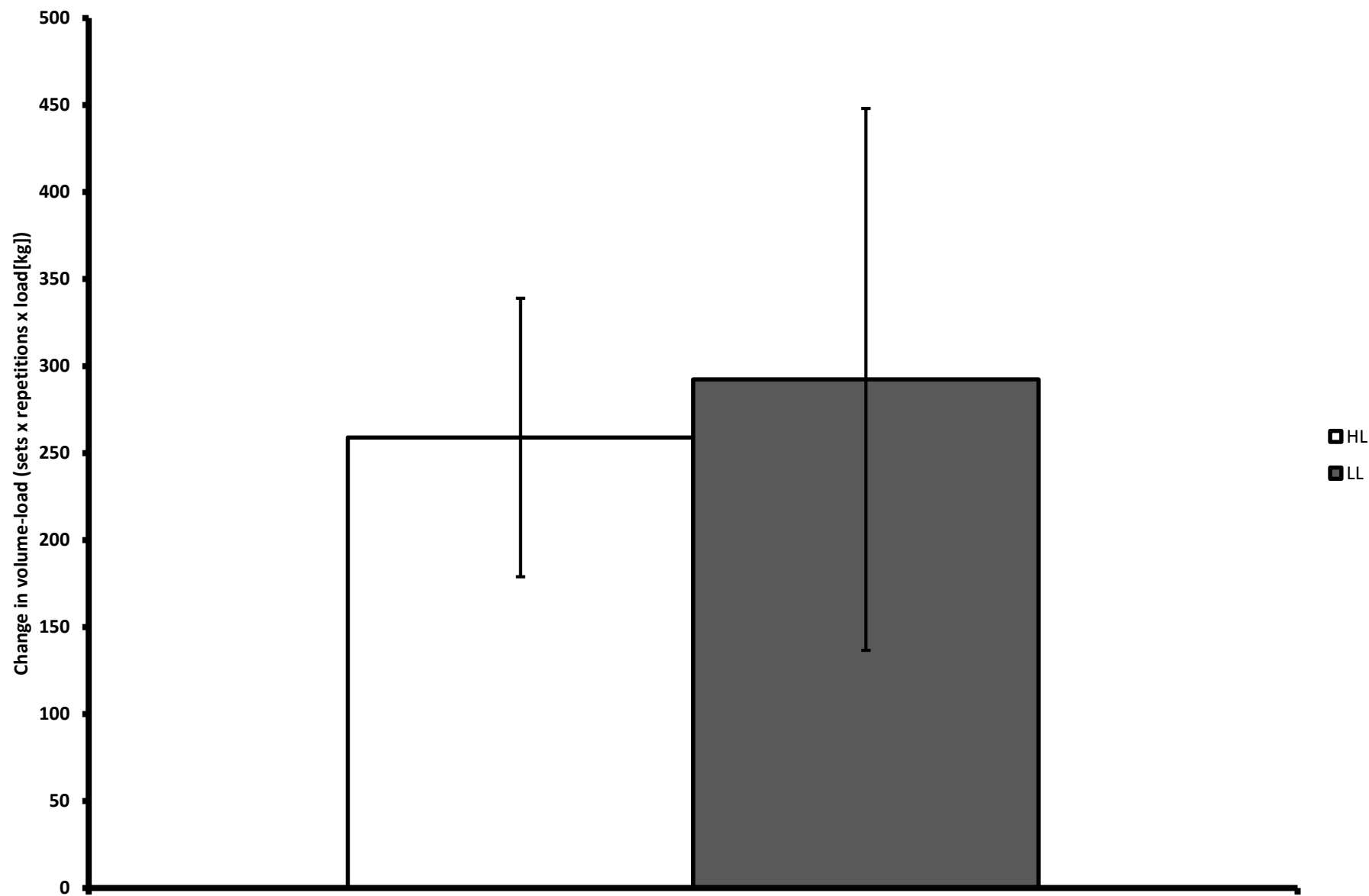
Figure 6. Scatter plots for change in volume-load and change in absolute endurance for A) HL group, B) LL group, and C) combined groups

A)

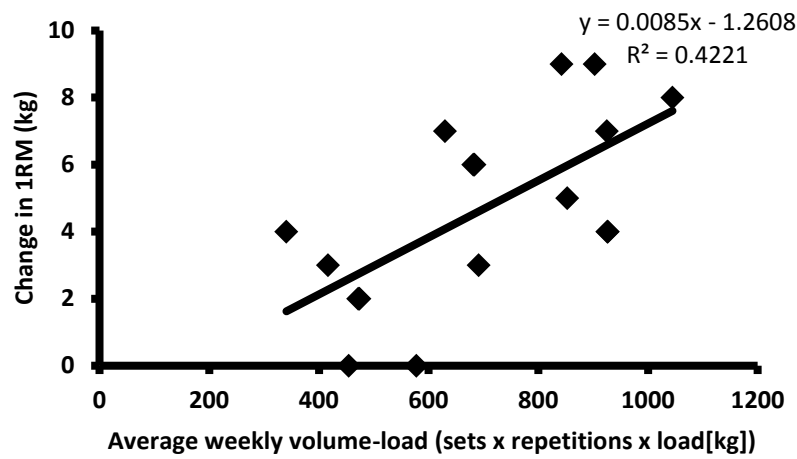


B)

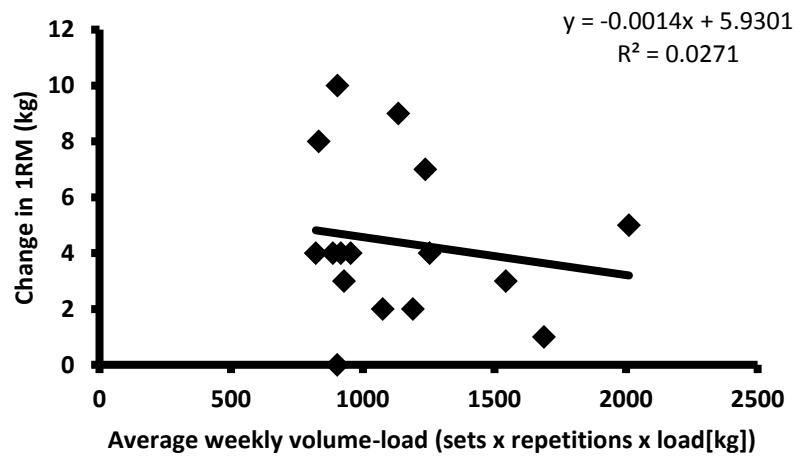




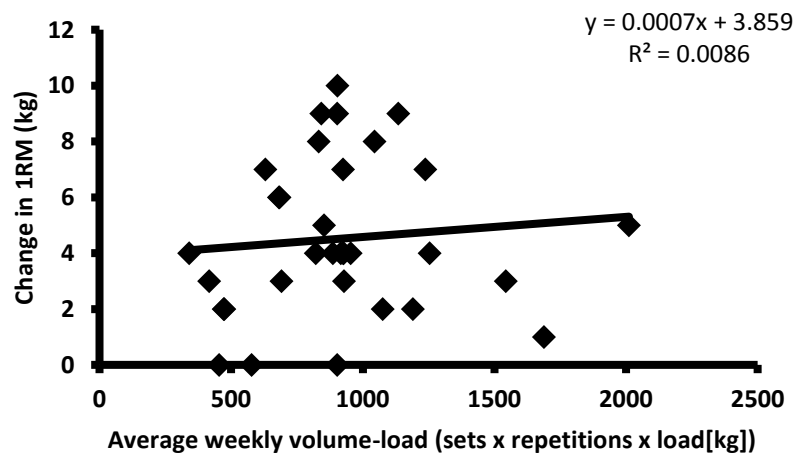
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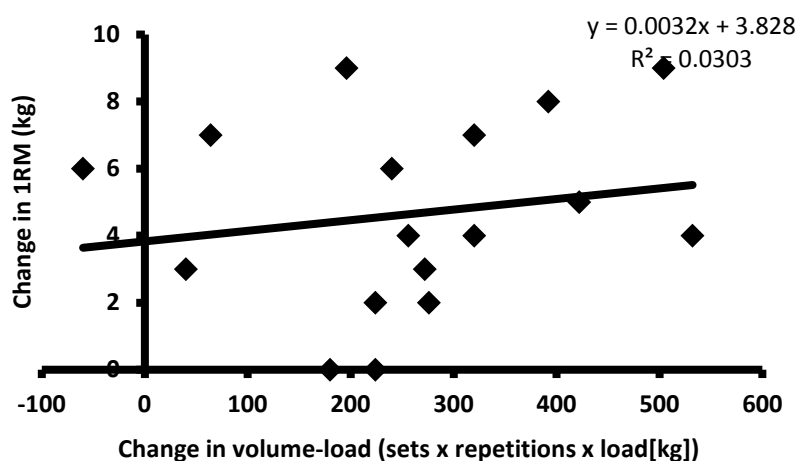
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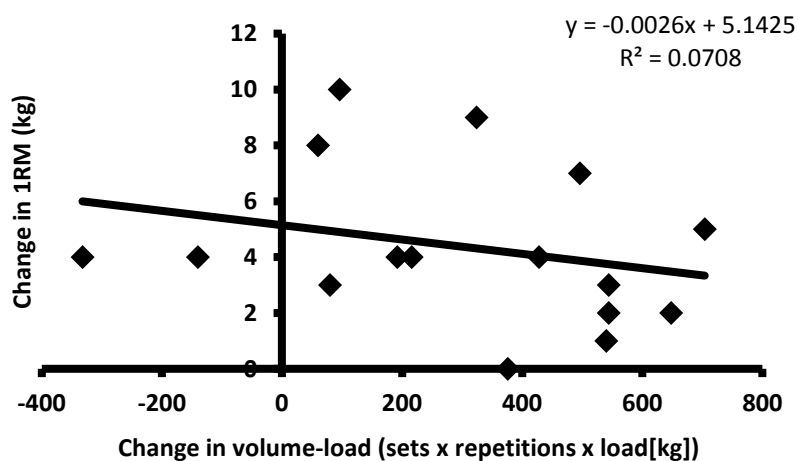
C)



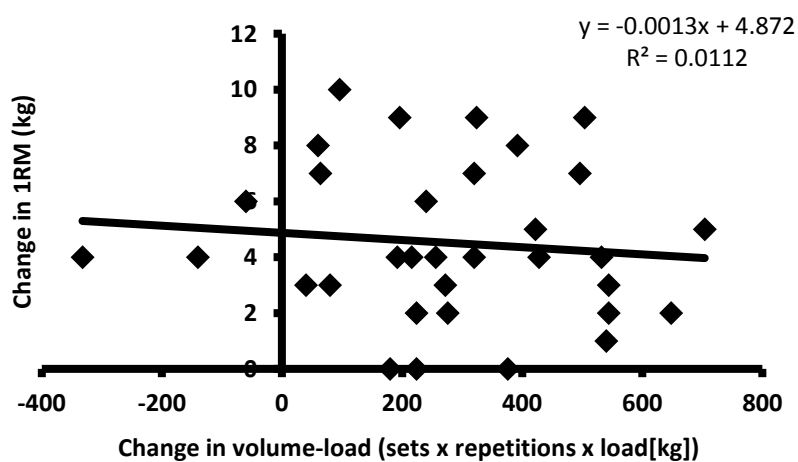
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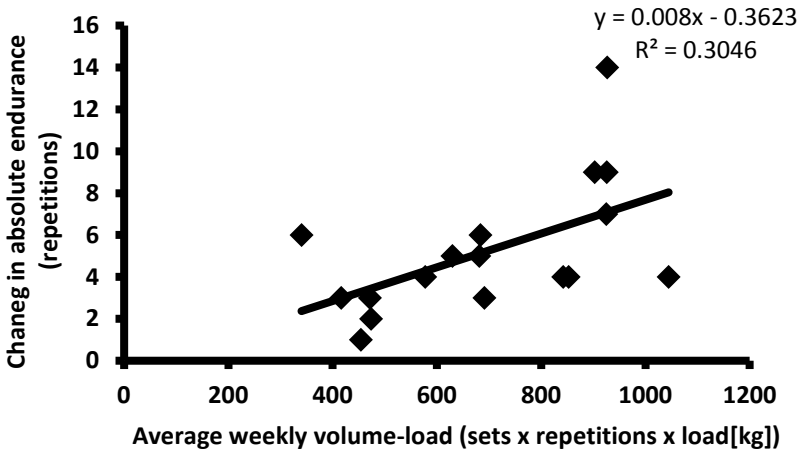
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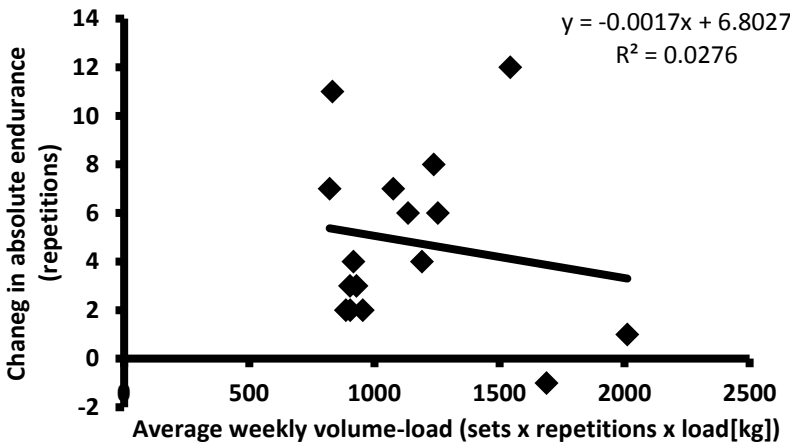
C)



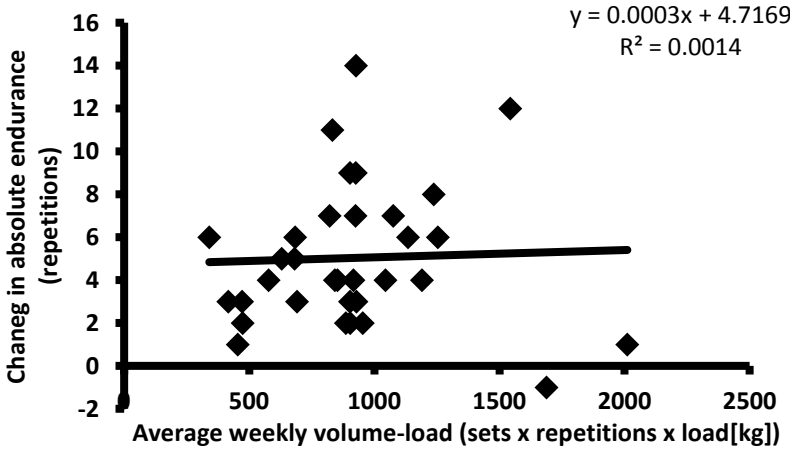
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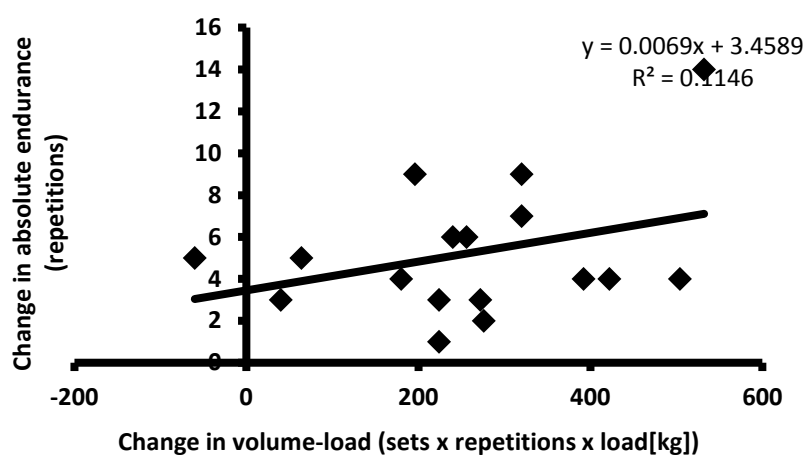
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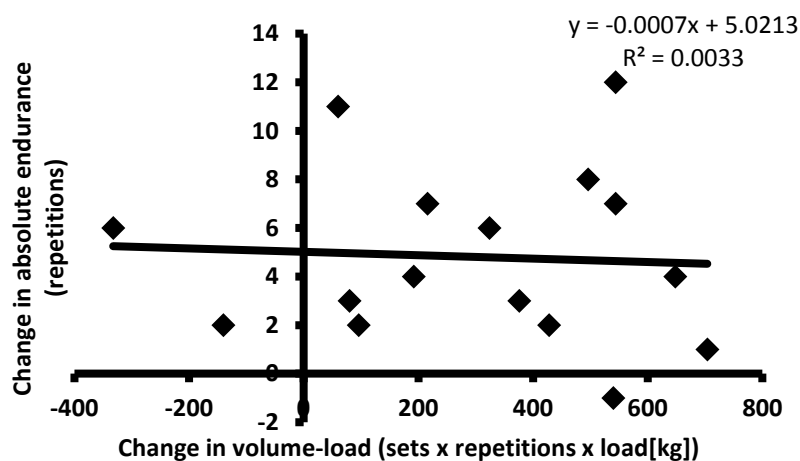
C)



A)



B)



C)

